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Tidal and Residual Currents Observations at the San Matías and San José Gulfs, Northern Patagonia, Argentina

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ABSTRACT

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Four current time series, collected at costal locations of the San Matías and San José gulfs, Argentina, are analyzed for tidal and residual currents. Tides dominate San Matías Gulf dynamics, accounting for more than 72% of the variance, whereas winds dominate at San José Gulf, explaining approximately 70% of the variance. Tides display a dominating semidiurnal regime, in compliance with what is know from the few tidal stations available and numerical simulations. At San Matías, coastal tidal currents speed increases northward, exceeding 0.6 m s^{-1} at San Antonio Este. Higher order harmonics because of nonlinear interactions are large; in every sampled site, M_4 and M_6 currents are stronger than the diurnal constituents and have amplitudes around 5% of those from M_2. At Las Grutas (San Matías Gulf), simultaneous wind observations were collected. Currents respond almost instantaneously to wind variability in the form of two modes. The first one results from winds blowing along the northwest–southeast axis and is very weak; the second one results from winds blowing from any other direction and is characterized by strong meridional currents. Even though bimodal patterns are typical of semienclosed basins, the characteristic wind directions in this gulf are not related with the orientation of its mouth but could result of the circulation in the form of two gyres suggested by numerical simulations. Energy peaks are observed at the 4 to 8 days' band and at around 12 and 20 days. Therefore, currents rapidly respond to wind variability in every timescale, from synoptic to intraseasonal.

ADDITIONAL INDEX WORDS: *Wind forced currents, current measurements, Northpatagonian Gulfs.*

INTRODUCTION

The Northpatagonian Gulfs (Figure 1) are a set of three gulfs located on the Argentinean Continental Shelf at the southwestern Atlantic at approximately 42° S and are known as Nuevo, San José and San Matías. The geometry and bathymetry of the area are complex, giving rise to a particular dynamics. The largest gulf, San Matías, communicates through a narrow mouth to the south with the smallest, San José, and through a broader mouth to the east with the open ocean. With an area of 19,700 km², it is one of the largest gulfs in South America. Its depth reaches 200 m and presents two relative maxima, one to the north and the other one to the south. Its mouth, 64 km wide and with depths shallower than 100 m, restricts the exchange with the shelf. The San José Gulf has an area of 814 km²; its east–west extension is 44.5 km, and it has a length of 18.5 km in the north–south direction. Its mouth, 6.8 km wide, is shallower than 80 m (SHN, 2000).

Three harbors are located at the San Matías Gulfs: San Antonio Oeste, San Antonio Este, and Punta Colorada (Figure 1). Two important resorts, Las Grutas and Playas Doradas (close to Punta Colorada), which are visited by thousands of tourists in summer, are located on its coasts as well. No permanent settlements exist in the San José Gulf coasts, even though shellfish divers, coastal collectors, and artisan fishermen, constitute a small-scale but highly rentable activity in the area. Los Pájaros Island, a nesting ground for numerous marine birds and a Natural Reserve, and the largest sea lions colony of Argentina, at Punta Bermeja (close to Viedma), are also located in this gulf.

Fisheries involve most of inhabitants in this region. It generates more than 1000 jobs and an annual income of more than US$20 million. The industry is in permanent expansion, being responsible for a large part of the sea food production and exportation in Argentina. During the last 5 years, the total catch in the area reached between 10 and 13.8 metric tons per year. Some of the species fished are *Merluccius hubb-*

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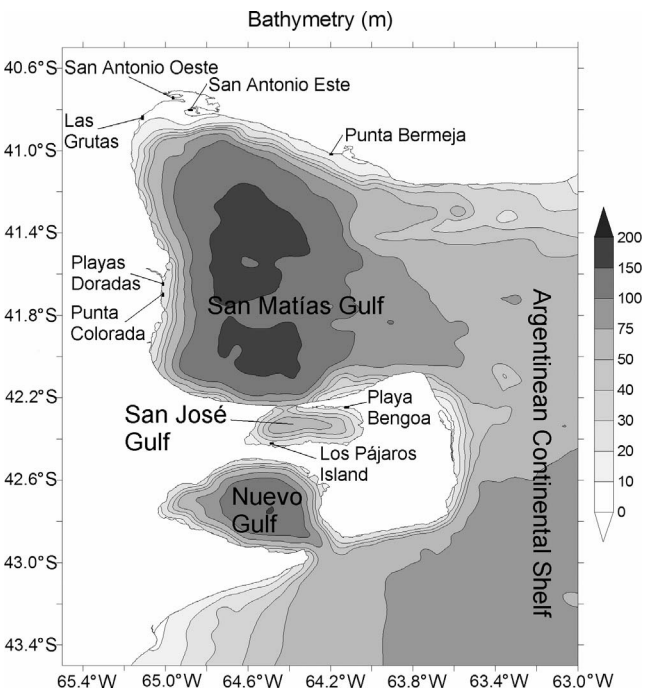

Figure 1. Bathymetry (in meters) of the Northpatagonian gulfs and main geographical references.

si, Macruronus magellanicus, Paralichthys spp., *Xistreuris rasile, Callorhinchus callorhynchus, Genypterus blacodes, Illex argentinus, Seriolella porosa, Parona sygnata, Squatina argentina, Mustelus* spp., and *Galeorhynus galeus.*

Besides their ecologic and economic importance, little is known about physical aspects of the oceanography of the gulfs and, in particular, about their circulation and forcings. Direct observations, collected in the northeast of the San Matías Gulf, indicate weak mean currents, of around 0.14 m s^{-1} at a depth of 25 m (Framiñan *et al.,* 1991). Nevertheless, tides in the region are among the largest in the world ocean, with amplitudes that exceed 9 m (SHN, 2008). This way, in this macrotidal system, tidal currents tend to be larger than mean currents, having large effects on vertical mixing and on properties distribution. In particular, the genesis of several fronts observed in the region in sea surface temperature satellite images has been connected to tides (Bava *et al.,* 2002; Franco *et al.,* 2008; Gagliardini and Rivas, 2004; Glorioso, 1987; Glorioso and Flather, 1995; Pisoni and Rivas, 2006; Rivas and Dell'Arciprete, 2000). Those fronts are associated with areas of high primary productivity and have, therefore, a large impact on the fisheries (Sabatini, 2004). They also have a large effect on determining the direction of the CO_2 fluxes (Bianchi *et al.,* 2005).

The few tidal observations in the area come from the scarce coastal tidal stations available: a total of four, located at San Antonio Este (40°48′ S, 64°53′ W), Río Negro (41°02′ S, 62°46′ W), Punta Colorada (41°42′ S, 65°00′ W), and Fondeadero San Román (San José Gulf) (42°15′ S, 64°14′ W). There are no direct observations of tidal currents in coastal areas of the gulfs, which, in turn, have the largest impact on human activity. Therefore, little is known about them or about the nonlinear interactions that probably occur in the area as a result of the complex geometry and bathymetry. With the aim of overcoming this limitation, the current time series were collected at three coastal locations in the San Matías Gulf and at one location in the San José Gulf. The data gathered span periods of between 1 and 3 month and provide the first opportunity of exploring tidal and residual currents in the coastal areas of the gulfs. The aim of this article is, therefore, to report those data and to provide a complete description of their statistics. It is expected that the results discussed here will contribute to the knowledge of the complex tidal dynamics in the area and will constitute a basis for the validation of numerical models.

DATA

Current time series were collected at three coastal locations of the San Matías and San José gulfs. The instrument was an Aanderaa RCM9 MkII, and the timespan of the time series is of approximately 1 month each. Given that intensive commercial fishing activities occur in the gulfs, the selection of sampling sites was conditioned, for the security of the instrument, to those places where permanent, visual control could be made. Sites were selected in terms of their economic importance as harbors, resorts, or fisheries. In this way, measurements were taken at Playa Bengoa (San José Gulf), a region where bivalves are collected; at Punta Colorada (San Matías Gulf), where a small harbor is located; and at San Antonio Este (San Matías Gulf), the most important harbor in the region. The location of the sampling sites can be observed in Figure 1.

During the first task, the current meter was deployed in Playa Bengoa, at 42°15′ S, 64°7′ W, in the middle of the water column, between May 20, 2006, and June 24, 2006, for a total of 35 days; the total depth at this location was of 10 m. During the second round, it was deployed in Punta Colorada at 41°41′ S, 65°00′ W, at the same depth, during the period July 4, 2006, to August 30, 2006, covering a total of 58 days. Finally, during the third campaign, the instrument was deployed in San Antonio Este at 40°47′ S, 64°53′ W, where the depth was of 9 m, between November 16, 2006, and December 10, 2006, a total of 25 days. During that last day, the array was towed by a ship entering the harbor, but the instrument was able to be recovered. As a result, unfortunately, this time series was shorter than the others. In every case, zonal and meridional current speed data were collected with a sampling period every half hour. The array consisted of an 80-kg iron body, with a subsurface buoy (25 kg buoyancy) to maintain the instrument in a vertical position, and a surface buoy to point out the position of the mooring.

An oceanic buoy collected oceanographic and meteorological observations during the period July 4, 2005, to November 11, 2005 (a total of 130 days). The buoy was deployed off shore Las Grutas (an important resort) at 40°56′ S and 65°04′ W (Figure 1), where the depth is 20 m. Wind speed and direction were measured with a Young, D4106–19, JR MA anemometer, and surface currents were measured with a Dopp-

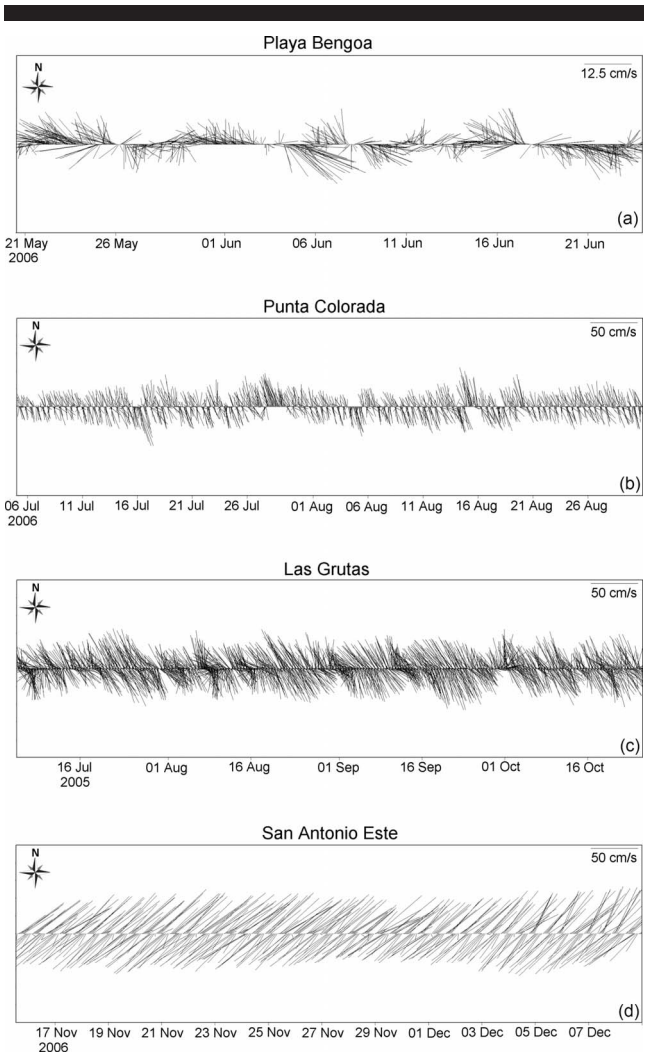

Figure 2. Stick diagrams of the currents time series collected at (a) Playa Bengoa, (b) Punta Colorada, (c) Las Grutas, and (d) San Antonio Este. Note that the scales used are not always the same and that each time series spans a different period.

ler current meter Aanderaa, DCS 3900R. The sampling period was 1 hour.

Data were corrected by magnetic declination, and quality control indicated that neither corrections nor filtering were necessary.

RESULTS

Tidal and Residual Currents

Stick diagrams of the four current time series are given in Figure 2.; note that the vector scales are different for the plots corresponding to the San Matías Gulf (Punta Colorada, Las Grutas, and San Antonio stations; Figures 2b–d) than for the one of the San José Gulf (Playa Bengoa station; Figure 2a). Also note that every series represents a different timespan. The first feature that emerges from this Figure is the large difference in the current speed and in the variability observed between the series collected at the San José Gulf and those gathered at San Matías Gulf. In particular, the series gathered at Playa Bengoa displays weaker currents and more temporal variability, as indicated by the continuous change in the currents' direction. The series collected at Punta Colorada, Las Grutas, and San Antonio Este, instead, displays a larger tendency to occur along an axis. This has a north–northwest to south–southeast orientation at Punta Colorada and Las Grutas, and a northeast to southwest orientation at San Antonio Este.

For a clearer interpretation, Figure 3 shows dispersion diagrams in the u–v space (zonal velocity–meridional velocity) of the same time series. These plots provide a better image of tidal current orientation and of the mean flow (at the observed level) along the observation period. At Playa Bengoa (San José Gulf), currents were weak, reaching maximum values of 26.4 and 15.6 cm s^{-1} for u (zonal velocity) and v (meridional velocity), respectively. The dot cloud (Figure 3a) spreads in west–northwest/east–southeast direction and is not centered at the origin but displaced toward the southeastern quadrant. This is an indication that a net wind-forced east–southeastward mean flow occurred during the period observed at the depth of the instrument; nevertheless, the shallowness of the location suggests that this flow is representative of the whole water column. The occurrence at this location of a strong wind-forced signal is consistent with the high variability in current direction observed in the stick diagram for this station (Figure 2a). Mean flow direction is better observed in Figure 4, which shows the progressive position vector diagrams of the four time series. Even though this kind of diagram does not exactly represent particle trajectories in nature, it provides a good image of the mean flow direction during the observation period. Note that even though the series collected at Playa Bengoa (spanning 35 d) is much shorter than the one corresponding to, for instance, Las Grutas (spanning 130 d), the progressive position-vector diagram shows a much larger mean flow for the first series than for the second. Nevertheless, the season when data were collected at those two stations was the same: fall for Playa Bengoa and fall–winter for Las Grutas. This suggests a larger influence of the wind and a smaller influence of the tide as forcings at San José than at San Matías Gulf.

The u–v dispersion diagrams for the data collected at San Matías Gulf (Figures 3b–d) show considerably larger values for the currents. Maxima were 23.8 and 44.3 cm s^{-1} for u and v, respectively, at Punta Colorada; 37.5 and 54.2 cm s^{-1}, respectively, at Las Grutas; and 57.5 and 54.8 cm s^{-1}, respectively, at San Antonio Este. At Punta Colorada and Las Grutas, the cloud of dots in Figure 3 and the stick diagrams in Figure 2 (b and c) show that currents at these locations align in a north–northwest/east–southeast direction. The dispersion diagram (Figure 3) indicates a slight displacement of the mean currents toward positive values of u, particularly at Punta Colorada. On the other hand, more dispersion is observed in Las Grutas than in Punta Colorada. This fact suggests a net eastward flow at both locations, but with larger variability at Las Grutas, which could derive from the fact that data at this last location were collected more offshore than at Punta Colorada. This result is more visible in the

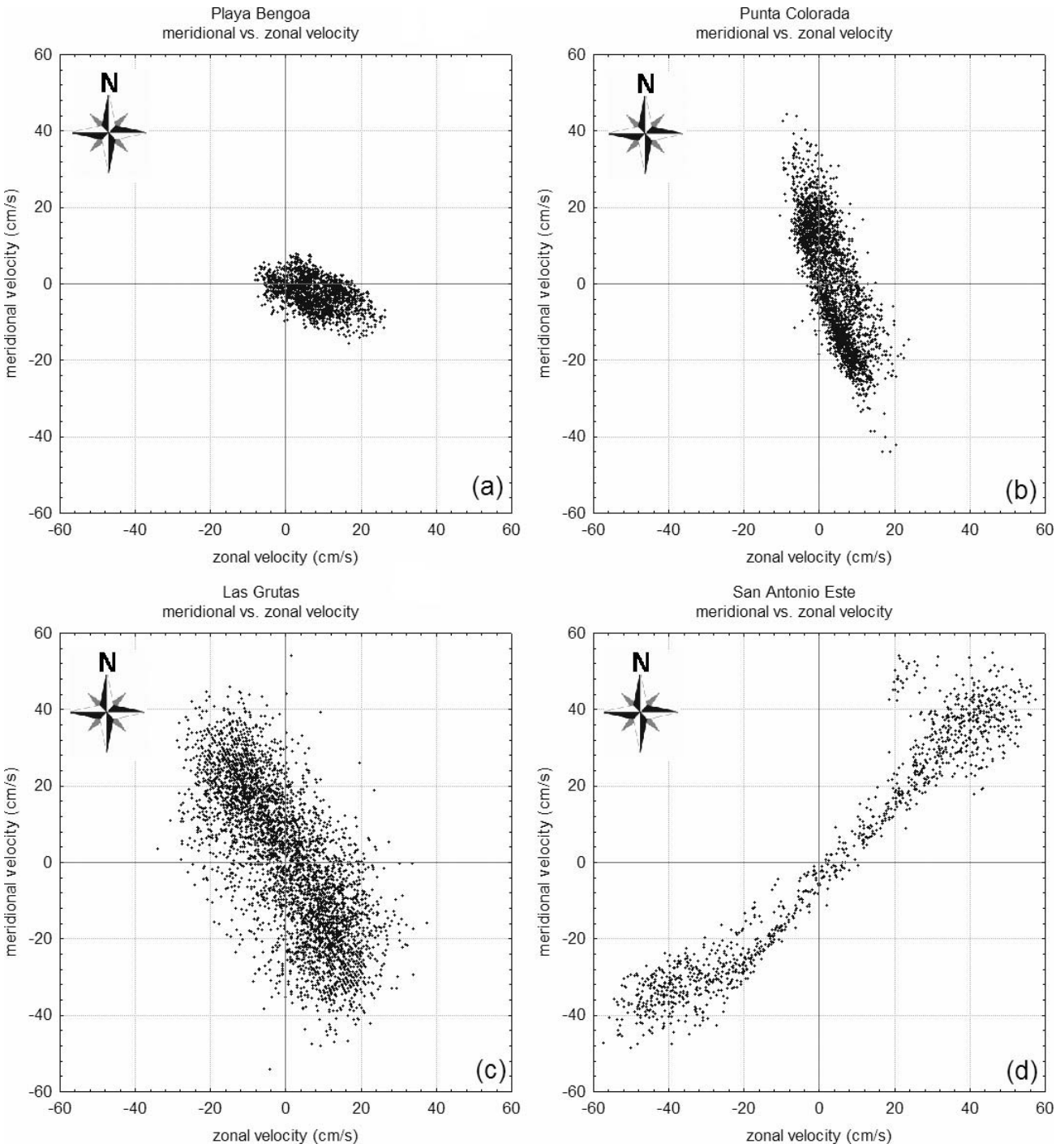

Figure 3. Dispersion diagrams in the *u*–*v* space (zonal–meridional velocity) of the currents time series collected at (a) Playa Bengoa, (b) Punta Colorada, (c) Las Grutas, and (d) San Antonio Este. Axes are in centimeters per second.

progressive position diagrams of Figures 3b and 3c, where, as a result of the variability observed in the currents, the mean flow results are much smaller in Las Grutas that in Punta Colorada. In contrast with the other two sites of the San Matías Gulf, the dispersion diagram (Figure 3d) and the stick diagram (Figure 2d) for San Antonio Este indicate that currents at this site have a preferential northeast–southwest direction. Nevertheless, a small mean northeastward flow still occurs, as revealed by the lower panel of Figure 4. Note that both Figure 2 and Figure 3 seem to indicate an increase

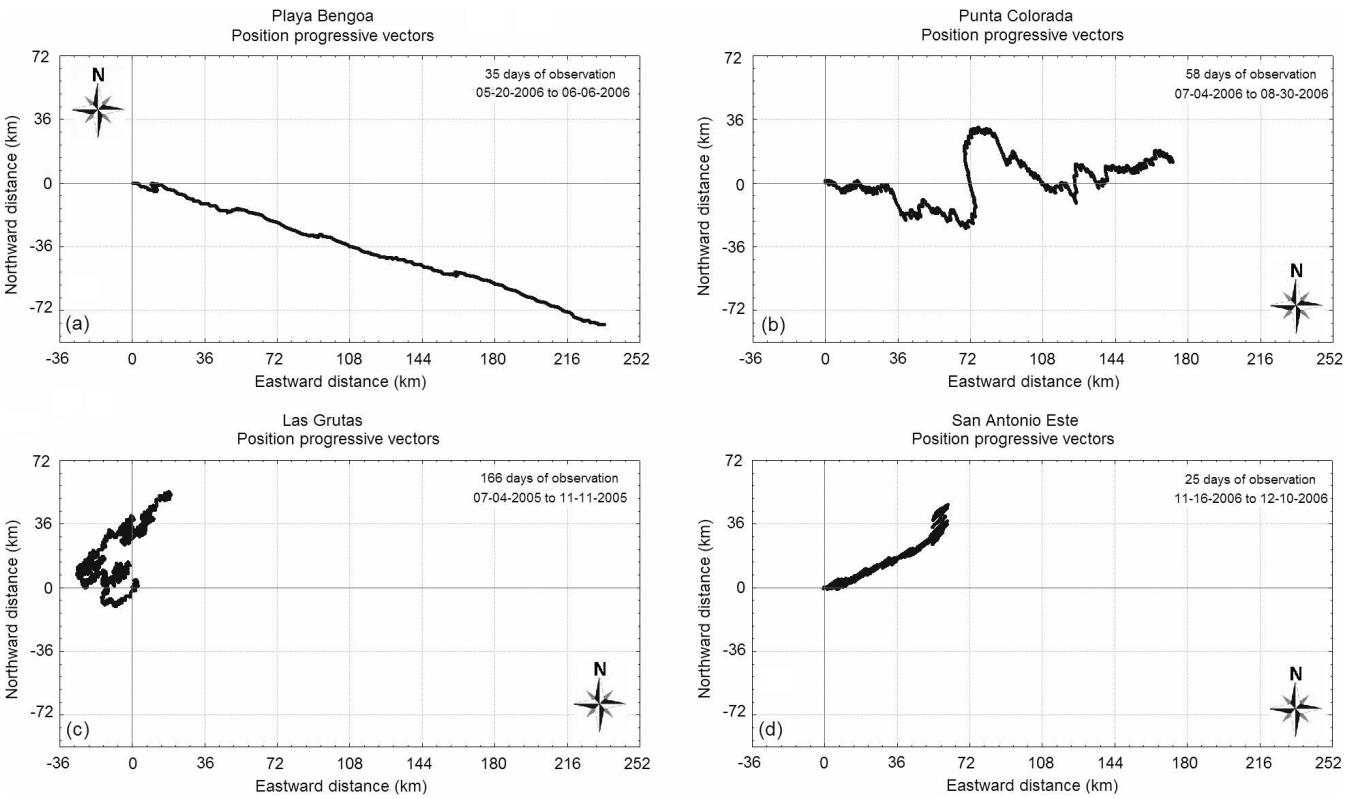

Figure 4. Position progressive vector diagrams of the time series collected at (a) Playa Bengoa, (b) Punta Colorada, (c) Las Grutas, and (d) San Antonio Este. Axes are in kilometers.

in the tidal current speed northward along the coast at the San Matías Gulf because values are larger at Las Grutas than at Punta Colorada and larger than those observed at these two last stations in San Antonio Este.

The time series collected at the four sampled sites were used to separate the tidal current (tidal ellipses) from the residual (wind forced) current by means of a harmonic analysis (Foreman, 1978). To evaluate the relative importance of tidal and wind-forced currents in the area, a variance analysis of both signals was carried out. Table 1 shows the total variance of each of the series and the percentage of variance accounted for the tidal and residual currents at each site.

Results indicate that, whereas tides account for most of the current variance in the three sites sampled at San Matías Gulf (with percentages more than 72% in every case), the opposite occurs in Playa Bengoa (San José Gulf), where tides account for less that 30% of the current variance. On the other hand, data collected at the San Matías Gulf show that the total variance increases with the speed, toward the northern part of the gulf along the coast. This way, our data suggest that, although the dynamics are dominated by tides at San Matías, they are dominated by winds at San José. This might be a consequence of its narrow mouth, which restricts the exchange with the largest San Matías Gulf, making the response to local winds the main signal there. In contrast, the wide mouth of the San Matías Gulf, almost as broad as the gulf itself (Figure 1), is less restrictive in the exchange with the open ocean. Our results, indicating relatively low mean velocities, are also consistent with the observations of Framiñan *et al.* (1991) for the northeastern part of the gulf, which revealed a mean current of only 14 cm s^{-1} at a depth of 20 m.

The major and minor semiaxis lengths, the inclination, and the phase of the tidal ellipses for the most important tidal

Table 1. *Total variance and percentages of variance accounted for the zonal (u) and meridional (v) tidal and residual (wind forced) currents at each of the four sampled sites.*

	Playa Bengoa		Punta Colorada		Las Grutas		San Antonio Este	
Component	*u*	*v*	*u*	*v*	*u*	*v*	*u*	*v*
Total currents variance (cm^2 s^{-2})	39.9	13.2	30.5	231.2	141.1	352.0	1089	931
% Tidal currents variance	30.6	24.8	72.3	75.7	80.9	87.8	92.4	94.3
% Residual currents variance	69.4	75.2	27.3	24.3	19.1	12.2	7.6	5.7

Table 2. *Major and minor axis (cm s^{-1}), inclination, and phase (degrees) of the tidal ellipses derived from the harmonic analysis of current time collected at each of the four sampled sites.*

	Playa Bengoa				Punta Colorada				Las Grutas				San Antonio Este			
Component	Major	Minor	Inclination	Phase	Major	Minor	Inclination	Phase	Major	Minor	Inclination	Phase	Major	Minor	Inclination	Phase
Q_1	0.74	0.29	151.50	189.70	0.29	−0.07	78.60	73.40	0.09	−0.03	45.60	340.80	—	—	—	—
O_1	0.21	−0.03	76.60	158.60	0.34	0.09	114.20	250.30	0.48	0.28	96.40	135.10	0.23	0.00	142.00	180.00
P_1	0.06	−0.03	34.00	259.20	0.05	0.04	104.50	330.10	0.24	−0.05	15.90	87.10	1.16	0.26	4.40	175.70
K_1	0.29	−0.20	36.20	256.90	0.17	0.14	106.60	327.80	1.06	−0.44	18.00	84.70	0.54	0.33	30.90	233.70
N_2	0.95	0.04	24.60	209.10	4.04	−0.62	103.30	160.20	6.83	0.60	121.40	302.50	1.92	0.88	33.00	231.40
M_2	4.93	−0.03	24.40	241.30	18.81	−3.01	108.30	184.20	28.25	3.68	120.60	345.30	60.42	2.46	42.70	262.60
S_2	0.58	−0.16	11.90	326.00	3.11	−0.32	108.50	266.60	6.36	0.34	120.40	59.10	15.83	−2.09	44.60	325.30
K_2	0.12	−0.04	170.90	139.80	0.63	−0.10	87.50	260.40	1.28	0.00	99.40	52.90	3.23	−0.59	23.60	319.10
M_4	0.32	0.00	45.60	79.20	1.49	0.07	95.60	111.50	1.57	0.73	140.60	257.80	6.43	−0.49	22.20	266.60
M_6	0.47	0.02	24.90	207.40	0.90	−0.13	116.30	34.60	1.11	0.06	113.20	242.20	6.29	−1.18	48.00	278.20
M_8	0.19	0.01	23.70	8.30	0.09	0.02	8.20	266.00	0.17	−0.04	175.70	223.00	2.12	−0.21	33.10	270.90
M_{10}	0.11	0.04	46.40	120.60	0.16	−0.04	94.40	308.80	0.29	0.06	115.40	221.10	0.54	−0.28	32.00	283.00

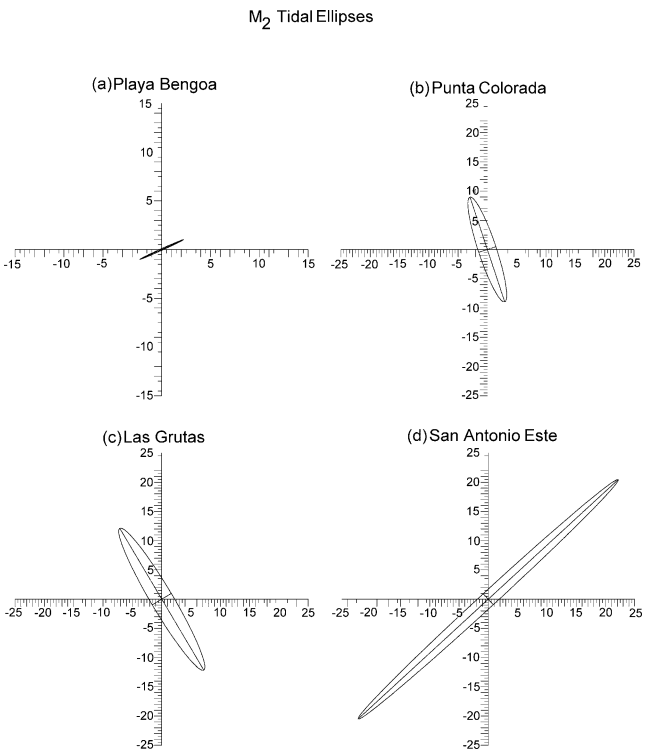

Figure 5. M_2 tidal ellipses derived from a harmonic analysis applied to the time series collected at (a) Playa Bengoa, (b) Punta Colorada, (c) Las Grutas, and (d) San Antonio Este. Axes are in centimeters per second. Note that the scales are not always the same.

current constituents, inferred from harmonic analysis of the data collected at the four sites, are shown in Table 2. Note that, because most of the series is short, the error in the estimation of the tidal ellipses increases for the small-amplitude constituents. Also, note that the tidal ellipses corresponding to Q_1 could not be inferred for the San Antonio series because of its shortness. Because of the length of the data series, P_1 was inferred from K_1, and K_2 from S_2, following the technique given by Schureman (1988). The first feature that emerges from Table 2 is the dominant semidiurnal character of the tide in the area, where the diurnal constituents' currents only reach a small fraction of the semidiurnal ones. This is consistent with what is known from tidal gauges in the area (SHN, 2008) as well as from numerical simulations (Glorioso and Flather, 1997). Secondly, a large difference between the tidal current speed in San Matías and San José gulfs is observed, consistently with the dispersion diagrams of Figure 3. Data indicate, also consistent with that Figure, an increase in tidal current speed northward along the San Matías Gulf coast. In effect, the amplitude of the M_2 tidal ellipses is 18.8 cm s^{-1} at Punta Colorada, 28.2 cm s^{-1} at Las Grutas, and 60.4 cm s^{-1} at San Antonio Este (Figure 5). Comparatively, tidal current in Playa Bengoa (San José Gulf) is small, with a maximum amplitude of only a few centimeters per second. With regard to the inclination of the dominant semidiurnal constituents, these results seem to be what was

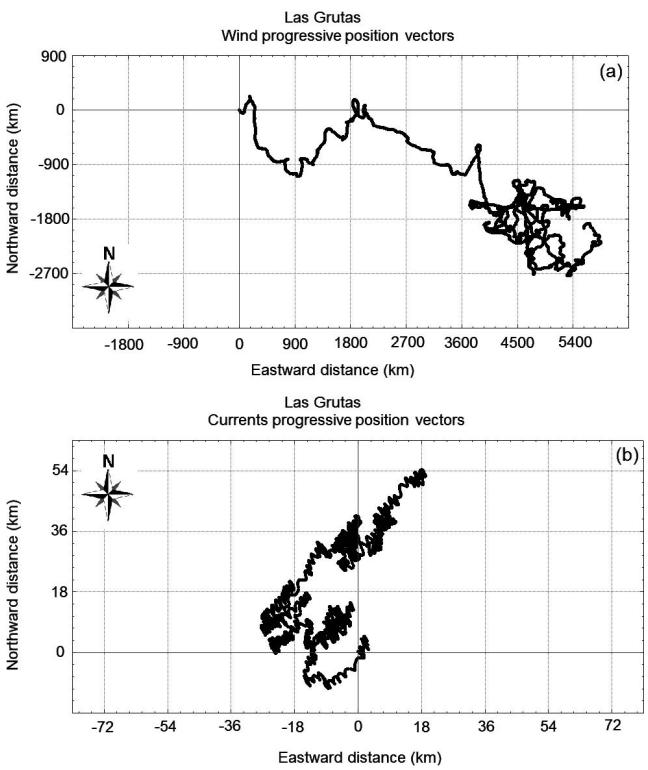

Figure 6. Position progressive vectors for (a) winds and (b) currents velocity of the time series at Las Grutas.

expected as a consequence of the geomorphology at each location, with an alignment of the ellipses with the coast. Finally, it is noticeable that the higher-order harmonics because of nonlinear interactions (M_4, M_6, M_8, and M_{10}) can be very important in the region. In all of the four sampled sites, our analysis indicates that M_4 and M_6 currents are stronger than those related to the diurnal constituents and that their amplitudes are around 5% of M_2.

Wind-Forced Currents in Las Grutas

As mentioned in the Introduction, besides currents, the oceanic buoy deployed in Las Grutas also measured the simultaneous wind speed and direction. Even though the availability of winds accompanied by currents at a single level does not allow a complete study of wind-forced currents, the unusual availability of direct simultaneous observations of these variables at the same site in the San Matías Gulf provides an excellent opportunity for observing the relationship between currents and winds and the involved scales of variability.

The wind progressive position vectors for the observed period in Las Grutas are shown in Figure 6a; to allow for a better comparison, Figure 6b displays the current progressive position vectors for this location in a different scale than that shown in Figure 4. It can be seen, in Figure 6, that during the observed period, wind had a dominant eastward component, consistent with the fact that this site is located southward 40° S and, therefore, under the influence of the Westerlies. A global comparison of this plot with the current progressive position vectors for this location (Figure 6a) suggests that ocean surface currents at this location tend to be mainly meridional and to the left of the winds. Nevertheless, currents seem to develop along different directions depending upon wind direction. To make this point clearer, Figure 7 shows the stick diagram of (a) the residual currents and (b) the winds for the observed period. In this Figure, the correspondence between wind and current variability is evident, suggesting a very fast response of currents to winds, at least in this shallow location of the San Matías Gulf. Note that during the first days of observation, winds with a northeastward component blew over the area forcing northward currents that are to the left of the winds. A few days later winds turned south–southeastward, but currents were southwestward, that is, to the right of the winds. Similar features can be observed at several other portions of the register, for instance, during the first days of August. The orientation of the wind-forced currents to the right or left of the winds, according to wind direction, is probably a geomorphologic effect, because the gulf is a semienclosed basin that cannot freely respond to the winds and because of the proximity of the coast to this sampling site.

To better analyze the relation between the variability of currents and winds at Las Grutas, Figure 8 shows the variance (energy) spectral density calculated from the currents (a and c) and from the winds (b and d) time series in that location. Consistent with the stick plot in Figure 7, which indicates that meridional currents dominate over zonal ones in this location, the currents' spectra show more energy associated to the meridional component. Nevertheless, for winds, variance is better distributed in both directions. This seems to be an indication that currents at this site have a more intense response to winds blowing from certain directions than from others, as has been observed in other semienclosed basins (see, for instance, Simionato *et al.*, 2004a, 2006; Wong, 2002). It is also evident in Figure 8, where the correspondence is between the scales of variability observed in currents and winds. In effect, besides the peak at around 12 hours because of the tide, the zonal current shows peaks at the bands between 4 and 8 days (96 to 192 h) and 10 and 20 days (288 to 528 h), whereas zonal wind exhibit peaks at the same bands. Note also the marked peak that the zonal wind component exhibits at approximately 24 hours. This is a signal of the strength of the breeze in the region, which, nonetheless, does not seem to produce a significant response in the ocean. For the meridional current component, besides the tidal peak at around 12 hours, peaks of variability are observed at the 4 to 8 days' band, with a maximum at 7 days (around 168 h), around 12 days (288 h), and around 20 days (480 h). the meridional wind component exhibits peaks at the same bands. The fact that meridional wind does not exhibit a peak at 24 hours is an indication that breeze in this area is mainly zonal, which, in turn, is consistent with the coastal orientation at this location (Figure 1). Note that in the tidal band, in both zonal and meridional current spectra, peaks at the semidiurnal band are much larger than at the diurnal one, in compliance the strong semidiurnal character of the

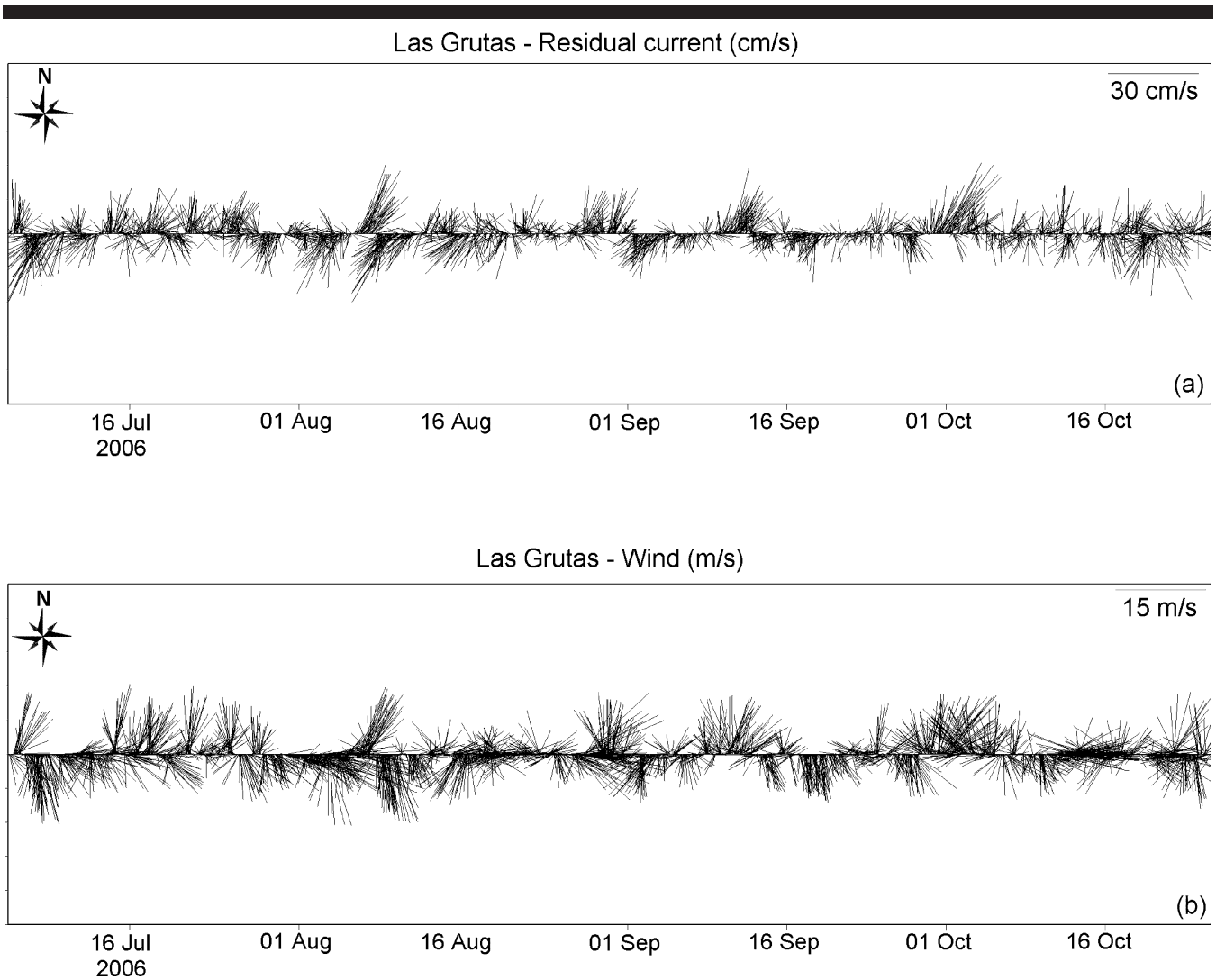

Figure 7. (a) Stick plot of the residual current (in centimeters per second) obtained by harmonic analysis of the time series collected in Las Grutas. (b) Stick plot of the winds (in meters per second) from the same site.

tide in this region (Glorioso and Flather, 1997). Finally, squared coherency and phase spectra between the zonal and meridional current components (Figures 8e and 8f) show that the wind-forced signal is highly coherent in both directions and is almost in phase for all the above-mentioned bands, except at 96 hours, when a phase lag of approximately 60° is observed between current components.

Even though the peaks in the diverse spectra of Figure 8 seem to suggest that zonal (meridional) winds force zonal (meridional) currents, a Principal Components (Empirical Orthogonal Function [EOF]) analysis, applied to both variables simultaneously, reveals that currents respond mainly to local meridional wind. In effect, the results of that analysis (Table 3) show that a first mode, accounting for 51% of the total variance, relates to both current components and the meridional wind, whereas the zonal wind is separated in a second mode. The factor loadings of the first mode (or correlation between the mode and each variable) are 0.76 for *u,* 0.85 for *v,* and 0.82 for the meridional wind, indicating the high correlation among these three variables. The second mode, mostly correlated to the zonal wind component, does not account for significant percentages of variance in the currents. Moreover, Figure 9, which shows the cross-correlation between the currents and wind components for different time lags, confirms that both current components are mostly forced by the meridional wind. This Figure also indicates the absence of a significant time lag between changes in the wind and the response in the currents. In this way, response to the wind is very energetic and fast in this location of the San Matías Gulf.

Finally, to provide an image of current response to wind direction at the location and depth of the Las Grutas site, Figure 10 shows current vectors, composed by wind sectors 45° wide, the first one centered at the North, for the whole

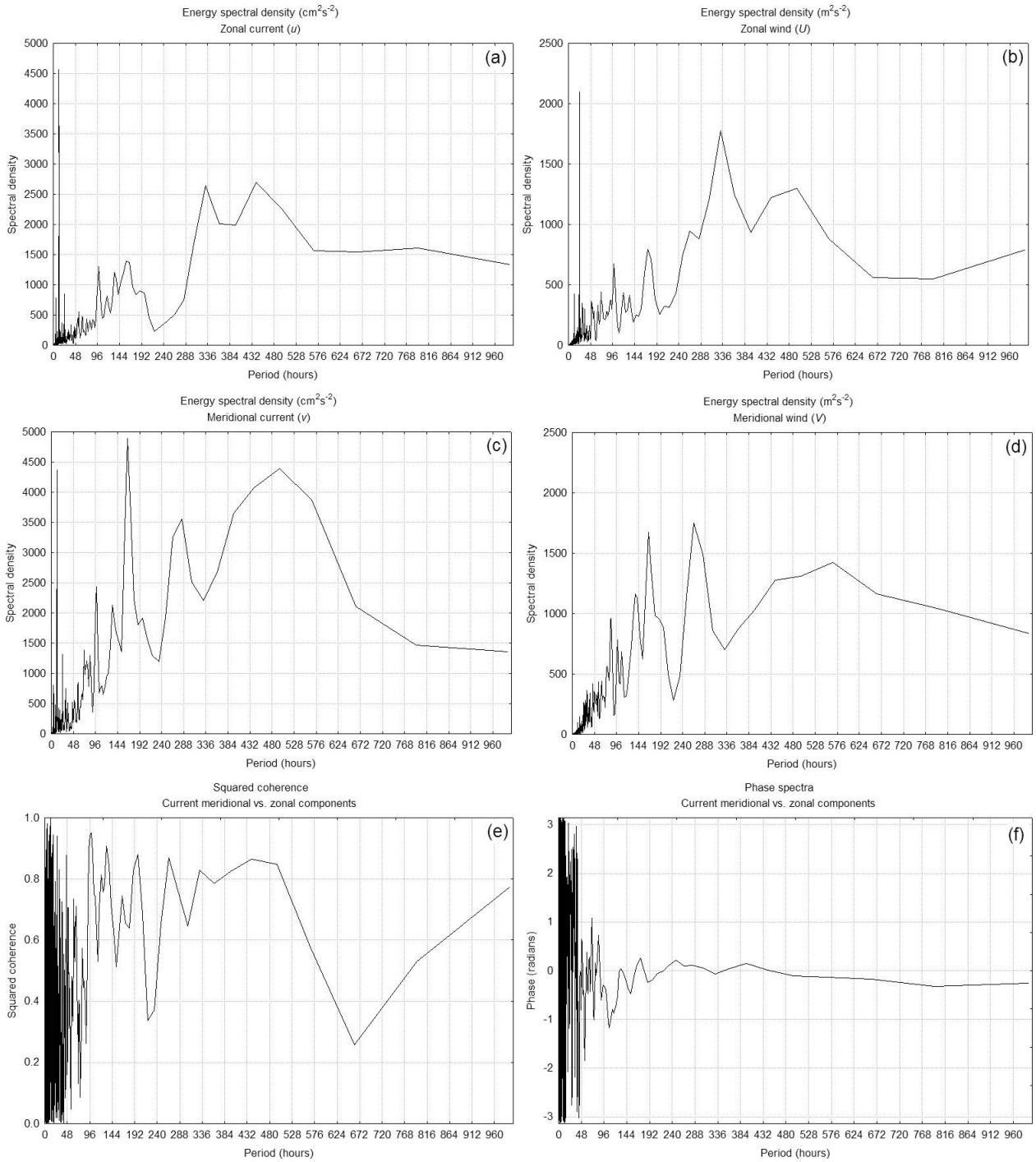

Figure 8. Energy spectral density of the currents and winds zonal (a and b) and meridional (c and d) components from the time series collected in Las Grutas and (e) coherence and (f) phase from the cross-spectra between the zonal and meridional currents components.

register. This Figure indicates that the Gulf at this location responds to most wind directions with a strong meridional current and a weak zonal one, except for northwesterly and southeasterly winds; for which, total currents response is very weak. This result does not seem to be skewed for the number of cases, given that every wind direction was well represented in the sample. Even though the minimum of 8.5% of the cases corresponded to southeasterly winds and the maximum of 16.1% of the cases corresponded to northerly winds, northwesterlies were represented by 13.6% of the cas-

Table 3. *Results of the Principal Components (EOF analysis) applied to the residual currents and wind data collected at Las Grutas.*

EOF Analysis—Factor Loadings	Factor 1	Factor 2
Residual zonal current (u)	0.76	0.18
Residual meridional current (v)	0.85	−0.15
Zonal wind	0.25	0.94
Meridional wind	0.82	−0.30
Percentage of explained variance	51%	25%

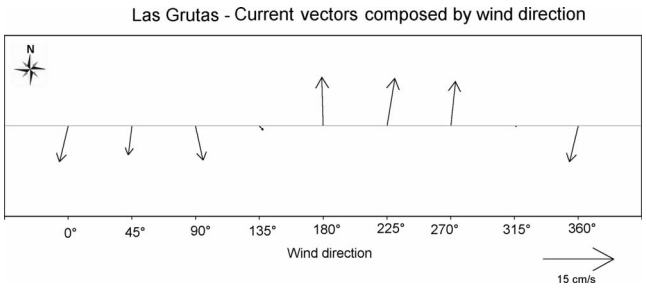

Figure 10. Current vectors composed by wind sectors 45° wide and centered at the north from the time series collected in Las Grutas.

es (Figure 11). Nevertheless, current speed could be influenced by mean wind speed for each wind direction, as revealed by Figure 10. In fact, even though southerly currents in our composite of Figure 9 were weaker that northerly currents, the observed mean wind speed for the corresponding direction displayed the same feature (Figure 11). Our results indicate, therefore, that, for winds blowing from between the north and the east, this site of the gulf develops a strong southward current, whereas for winds blowing form the south to the west, it develops a strong northward current, and almost no response results for winds from the southeast–northwest direction. Because zonal wind-forced currents are small at this location, errors in their estimation are probably larg-

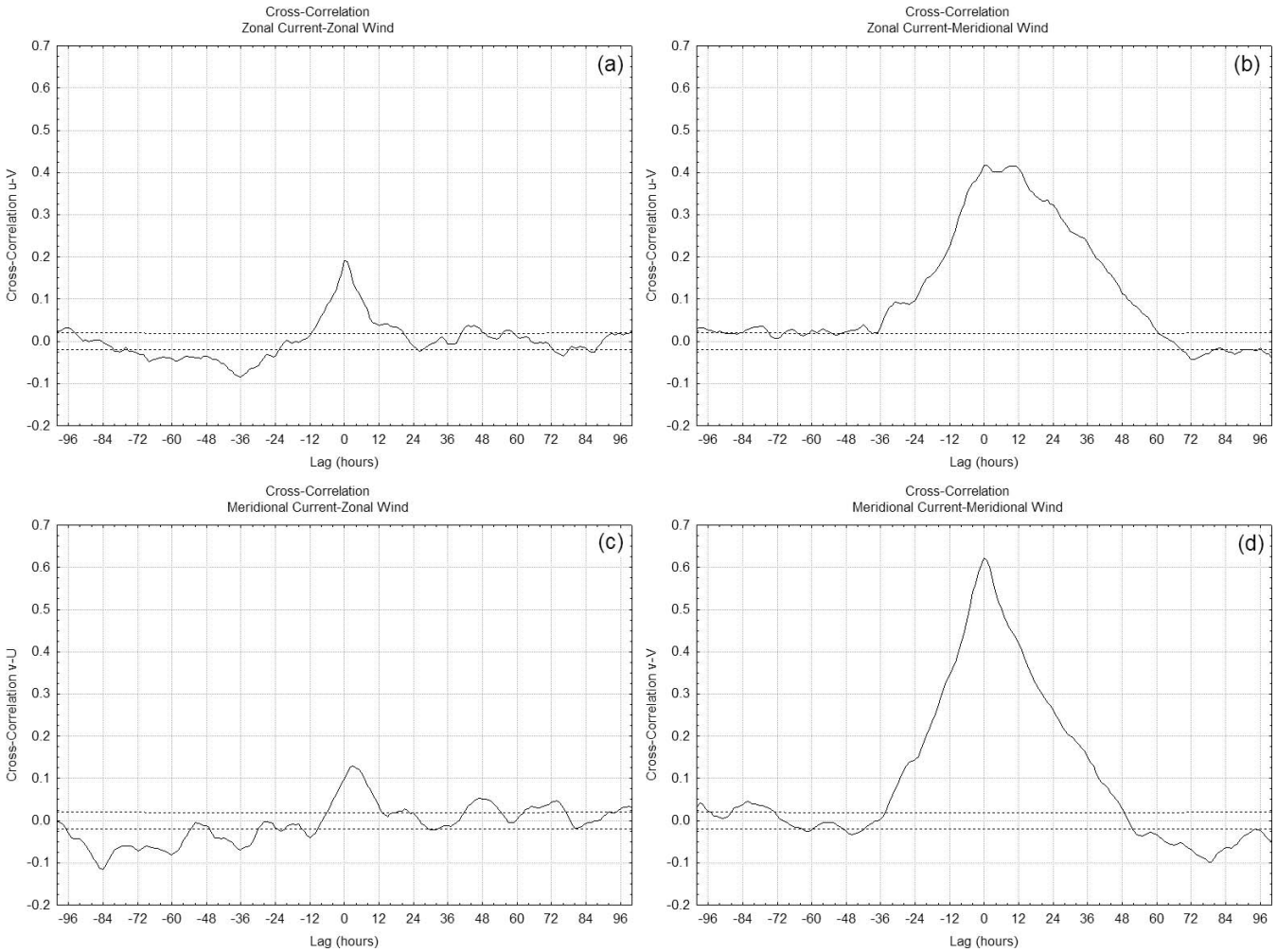

Figure 9. Cross-correlation between currents and winds of the time series collected in Las Grutas: (a) zonal current and zonal wind, (b) zonal current and meridional wind, (c) meridional current and zonal wind, and (d) meridional current and meridional wind.

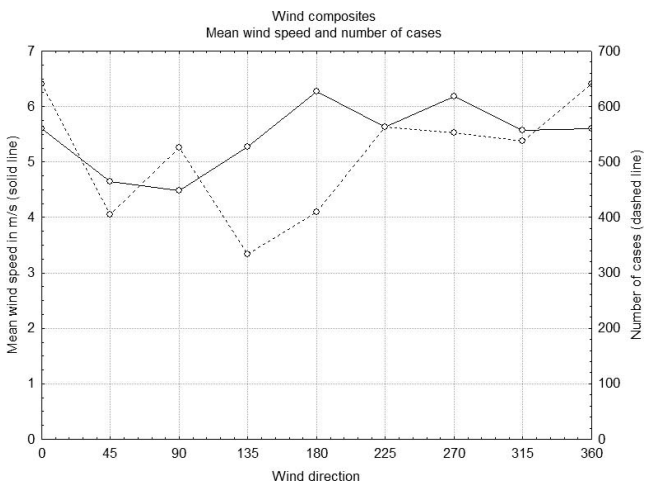

Figure 11. Composite of mean wind speed by wind direction in sectors 45° wide centered at the north (left axis, solid line) and number of cases used for each composite (right axis, dashed line).

er. Nevertheless, they seem to be able to occur in opposition to zonal wind, as is the case, for instance, for winds from the 90° sector. The bimodal pattern of response to winds detected in this series has been observed in other semienclosed basins (see, for instance, Simionato *et al.*, 2004a, 2006; Wong, 2002); nevertheless, wind directions associated to one or another mode of response are usually related to the orientation of the mouth. This does not seem to be the case here, given that the gulf mouth has a north–south orientation, whereas currents seem to respond, in one mode, to winds blowing along the northwest–southeast axis and, in another mode, to winds from any other direction. A pattern of circulation in the form of two gyres, one cyclonic to the north and the other anticyclonic to the south has been find in this gulf (Beier and Akaprahamyan, 1991; Beier, Fiore, and Orlanski, 1989) in numerical simulations; the occurrence of the northern gyre has been also reported from observations (Piola and Scasso, 1988). Likely, the pattern of the response observed in our data is a result of this fact and related to the geomorphologic features of the area.

CONCLUSIONS

In this article, four current time series, with time spans of between 1 and 5 months, collected at several locations of the San Matías and San José gulfs, were analyzed for tidal and wind-forced variability, providing the first information about currents in coastal locations of those gulfs. Results indicate that coastal currents in San Matías Gulf are stronger than in San José Gulf; in fact, in this last gulf, current speed is about one-fourth of that observed in the first gulf, with typical values less than 15 cm s^{-1}. As a result of the narrow mouth that communicates between them, the interaction between San José and San Matías gulfs seems to be quite restricted, and therefore, tidal currents are of small amplitude in the inner gulf. There, instead, wind-forced currents seem to dominate the energy balance. In every location, independent of the season when data were collected, an eastward water mean flow was observed. This is probably a result of the fact that both gulfs are located in the Westerlies region. In the San Matías Gulf, tidal currents account for more than 70% of the total variance at every location. Coastal tidal currents increase to the north, and in the northernmost location, they account for more than 90% of the variance. Tidal currents are dominated by the semidiurnal constituents, in compliance with what is know from observations (SHN, 2008) and numerical simulations (Glorioso and Flather, 1997) for the Patagonian Shelf, whereas diurnal constituents account for a much smaller percentage of the variance. An alignment of the tidal ellipses with the coast line is observed at every location. Our analysis also indicates that higher-order harmonics from nonlinear interactions can be very important in the region. In all four of the sampled sites, M_4 and M_6 currents were stronger than those related to the diurnal constituents, and their amplitudes were around 5% of M_2. The importance of nonlinear effects in the Argentinean Shelf was noticed by several authors from observations and numerical simulations (see, for instance, Simionato *et al.,* 2004b). Nevertheless, the data analyzed in this article have provided the first opportunity for a quantification of those effects at coastal locations of the Northpatagonian Gulfs.

The instrument deployed at Las Grutas (San Matías Gulf) measured simultaneous wind speed and direction, providing an unusual opportunity to evaluate wind-forced currents in the area and their scales of variability. Even though the analysis is restricted to the level of the instrument, the results are very useful and illustrate the particular way in which this gulf responds to winds. It was found that currents respond almost instantaneously to wind variability. The signal is dominated by meridional winds and seems to be in the form of two modes. One of them results from winds blowing in the northwest–southeast axis and is very weak; the other one results from winds from all the other directions and is characterized by strong meridional currents. Even though this kind of bimodal pattern is typical of semienclosed basins, the characteristic wind directions do not seem to be related with the orientation of the gulf mouth. The gulf develops a strong response to meridional winds but a weak one to the zonal winds and seems to reflect all the observed wind scales of variability. Energy peaks are observed at the 4 to 8 days' band with a maximum at 7 days (around 168 h), at around 12 days (288 h), and at around 20 days (480 h). Therefore, currents seem to rapidly respond to wind variability in synoptic to intraseasonal timescales.

Evidently, our observations and results cannot provide a complete picture of the circulation in these gulfs, and it is evident that more long-term observations of, at least, currents and winds, are needed for a better understanding of their dynamics. Nevertheless, these data have provided a large amount of information, contributing to the knowledge of the complex tidal and wind-forced dynamics in the area and constituting a basis for model validation. These simulations, which are envisaged for the immediate future by several research groups in Argentina, including ours, would help to complement the few observations available, to compose a

clearer conceptual picture, and to suggest the most important areas for further observational efforts.

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□ **FOREIGN RESUME** □

Se estudian las corrientes de marea y residuales de cuatro series de corrientes colectadas en sitios costeros de los golfos San Matías y San José, Argentina. En el golfo San Matías, la marea domina la dinámica, explicando más del 72% de la varianza, mientras que los vientos dominan en el San José, explicando aproximadamente el 70% de la varianza. Las mareas muestran un régimen esencialmente semidiurno, en concordancia con lo que se sabe de las pocas estaciones mareográficas disponibles y de simulaciones numéricas. En San Matías, la velocidad de las corrientes costeras crece hacia el norte, excediendo los 0,6 m s^{-1} en San Antonio Este. Los armónicos de mayor orden, debidos a interacciones no lineales son grandes; en todos los sitios muestreados las corrientes debidas a M_4 y M_6 son mayores que las componentes diurnas y tienen amplitudes de alrededor del 5% de M_2. En Las Grutas (golfo San Matías) se colectaron observaciones de viento simultáneas. Las corrientes responden casi instantáneamente a la variabilidad del viento en forma de dos modos. El primero resulta de vientos que soplan a lo largo del eje noroeste-sudeste y es muy débil; el segundo resulta de vientos que soplan de todas las otras direcciones y está caracterizado por fuertes corrientes meridionales. Aunque los patrones bimodales son típicos de cuencas semicerradas, las direcciones características del viento en este golfo no están relacionadas con la orientación de su boca, sino que podría resultar de la circulación en forma de dos giros sugerida por simulaciones numéricas. Se observan picos energéticos en la banda de 4 a 8 días y alrededor de 12 y 20 días. De esta manera, las corrientes responden rápidamente a la variabilidad del viento en todas las escalas temporales, de la sinóptica a la intra-estacional.